

Final Report on
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PHYSICS OF MAGNETOSPHERIC BOUNDARY
LAYERS

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1 Introduction

In December 1990 Professor Chris Goertz was awarded NASA grant NAGW-1483 on “Magnetospheric Boundary Layers” under the Space Physics Theory Program. The two themes of the research program were that, first, magnetospheric boundary layers link disparate regions of the magnetosphere-solar wind system together, and second, the global behaviour of the magnetosphere can be understood only by understanding its internal linking mechanisms and those with the solar wind. Accordingly the research program involved simultaneous research on the global, meso-, and micro-scale physics of the magnetosphere and its boundary layers. These boundary layers include the bow shock, the magnetosheath, the plasma sheet boundary layer, and the ionosphere. Analytic, numerical and simulation projects were performed on these subjects, as well as comparisons of theoretical results with observational data. The original personnel involved in this effort were Professors Chris Goertz and Bob Smith, Doctors Paul Hansen, John Lyon, and Ebraahim Moghaddam-Taaheri, and graduate students Mr. Barry Harrold, Mr. Bob Holdaway, Mr. Lyle Jalbert, Mr. Xin Li, Mr. Gang Lu, and Mr. Lin-hua Shan. Three of these students obtained their Ph.D. degrees, and two of them their M.S. degrees, under the aegis of this grant. Doctors Ken-ichi Nishikawa and Iver Cairns became involved in the research program in 1991.

The deaths of our colleagues Chris Goertz, Lin-hua Shan, Bob Smith, and Gang Lu on 1 November 1991 obviously had a major effect on the research direction and productivity of the Group. Prior to this time the Group was focussed primarily on the prediction of geomagnetic activity (Goertz, Shan and Smith), global MHD simulations (Lyon, Goertz), Alfven resonance heating (Goertz, Hansen, Harrold, Holdaway, and Smith), and the Critical Ionization Velocity (CIV) effect (Moghaddam-Taaheri and Goertz). The grant passed into the stewardship of Dr. John Lyon and then, in May 1993, Dr. Iver Cairns. The remaining members of the Group worked actively together on their joint interests, with primary attention to global MHD and PIC simulations (Lyon, Cairns, Nishikawa), Alfven resonance heating (Hansen, Harrold, and Holdaway), and CIV physics (Moghaddam-Taaheri and Nishikawa). Very good progress was made in these areas, with 20 papers being published. as detailed below. Unfortunately the grant was not renewed in 1993.

The remainder of this Final Report is organized by areas of interest, with brief summaries of each paper’s primary motivation and results and a reference. Appendix A lists the personnel involved, Appendix B lists the graduate students funded, Appendix C identifies the papers published, and Appendix D contains reprints or photocopies of papers produced under the aegis of this grant.

2 Research Accomplishments

During the grant period significant accomplishments were achieved in a variety of research areas from geomagnetic activity to global magnetosphere-solar wind simulations to micro-physics. These accomplishments will now be described in turn.

2.1 Geomagnetic activity

The prediction and explanation of geomagnetic activity, such as substorms and variations in the AE, AU, AL, and Dst indices, remains one of the primary goals of magnetospheric physicists and space science as a whole. Motivated by the earlier ‘thermal catastrophe’ model for substorms [Smith et al., 1990], chaos theory formed a significant portion of the research [Goertz et al., 1991, Shan et al., 1991a,b]. The development of a model for substorms, with a correlation coefficient of order 90% with the observed AE time series, also sparked a lot of interest in the field [Goertz et al., 1993].

Goertz et al. [1991] developed a simple dynamical model of the magnetotail in which the electric field in the current sheet evolves due to the solar wind-induced electric field at the magnetopause and the temperature-dependent entropy of plasma in the plasma sheet. The entropy varies due to non-adiabatic heating, resulting from resonant absorption of Alfvén waves, and the feedback between temperature and entropy change leads to chaotic dynamics.

- **C.K. Goertz, R.A. Smith, and L.-H. Shan**, Chaos in the plasma sheet, *Geophys. Res. Lett.*, 18, 1639, 1991a.

Shan et al. [1991a] employed the embedding-dimension method to analyze time series of geomagnetic indices and thereby find the correlation dimension ν of the system of dynamical equations governing geomagnetic activity. They found $\nu \sim 2.4$ for the AE index. The hope of obtaining a finite set of equations to describe geomagnetic activity therefore remains possible. Shan et al. [1991b] demonstrated that the existence of a periodicity in the AE power spectrum introduces an extra degree of freedom in the data and increases the correlation dimension.

- **L.-H. Shan, P. Hansen, C.K. Goertz, and R.A. Smith**, Chaotic appearance of the AE index, *Geophys. Res. Lett.*, 18, 147, 1991a.
- **L.-H. Shan, C.K. Goertz, and R.A. Smith**, On the embedding-dimension analysis of AE and AL time series, *Geophys. Res. Lett.*, 18, 1647, 1991b.

Goertz et al. [1993] incorporated their 1991 magnetotail model into an analytic model for the directly driven component of solar wind-magnetosphere-ionosphere coupling. The model included front-side magnetic reconnection and magnetosphere-ionosphere coupling due to Alfvén waves induced by changes in the magnetospheric electric field. They used

the model to predict the AE index for a two day period in May 1979 using the solar wind convection field as the input. Figure 1 compares the predicted (thin line) and observed (thick line) AE indices. The cross-correlation coefficient for these series is greater than 0.9. Most geomagnetic activity during this period is therefore directly driven by the solar wind. Difficulties reconstructing Dr. Shan's numerical code have prevented extension of this work. It is also true that the model works less well during other events. Nevertheless, Goertz et al.'s model is widely recognized as an outstanding accomplishment.

- **C.K. Goertz, L.-H. Shan, and R.A. Smith**, Prediction of geomagnetic activity, *J. Geophys. Res.*, 98, 7673, 1993.

2.2 Global magnetosphere-solar wind interactions

State-of-the-art global, 3-D, ideal MHD simulations of the ionosphere-magnetosphere-solar wind simulation were performed by Lyon, Fedder and collaborators to investigate substorm phenomena [Fedder et al., 1991; Lyon and Fedder, 1994; Fedder and Lyon, 1994]. Fedder et al. [1991] investigated the efficiency of frontside magnetic reconnection as a function of the IMF clock angle. Fedder and Lyon [1994] demonstrate that the Earth's magnetosphere is stretched at least $165R_e$ downtail for Northward IMF (therefore, no plasmoids or substorms), and that simulation domains must be at least this big to assure self-consistent current and convection systems. Lyon and Fedder [1994] simulated a substorm event stimulated by the IMF turning southward. They demonstrated that the simulations are qualitatively and semi-quantitatively consistent with available observations. These authors are continuing to pursue this research under other sources of funding.

- **J.A. Fedder, C.M. Mobarry, and J.G. Lyon**, Reconnection voltage as a function of IMF clock angle, *Geophys. Res. Lett.*, 18, 1047, 1991.
- **J.A. Fedder and J.G. Lyon**, The Earth's magnetosphere is $165R_e$ long: or self-consistent currents, convection, magnetospheric structure and processes for northward IMF, *J. Geophys. Res.*, in press, 1994.
- **J.G. Lyon and J.A. Fedder**, Global simulation of a southward turning in the IMF and its comparison with substorm morphology, *Geophys. Res. Lett.*, submitted, 1994.

Drs. Cairns and Lyon used an adapted version of the above global 3-D MHD simulation code to study the 3-D location and characteristics of the bow shock and magnetosheath [Cairns and Lyon, 1994; Lyon, 1994]. The code uses a hard, infinitely conducting inner boundary at the magnetopause's location (with ionosphere-magnetosphere coupling turned off) so as to mimic and allow fair and detailed comparison with previous gasdynamic simulations. Extremely exciting results were found [Cairns and Lyon, 1994], including the demonstration that the magnetic field orientation affects the standoff distance of the

shock, that the standoff distance is much more distant at low Alfvén mach numbers than predicted by gasdynamic theory or phenomenological ‘MHD’ variants thereof, and that a new intrinsically MHD model for shock locations could explain the simulation results with excellent accuracy. Significant progress in constructing an analytic MHD theory for the standoff distance and magnetosheath thickness was also made [Cairns and Grabbe, 1994]. Comparison with Lyon’s [1994] MHD simulations of the magnetosheath is expected in the future. Additional analytic and MHD simulation work on the bow shock’s location and shape is ongoing.

- **J.G. Lyon**, MHD simulations of the magnetosheath, *Adv. Space Res.*, *14*, (7)21, 1994.
- **I.H. Cairns and C.L. Grabbe**, Towards an MHD theory for the standoff distance of Earth’s bow shock, *Geophys. Res. Lett.*, *21*, 2,781, 1994.
- **I.H. Cairns and J.G. Lyon**, MHD simulations of Earth’s bow shock at low Mach numbers: standoff distances, *J. Geophys. Res.*, submitted, 1994.

In addition, Dr. Nishikawa developed a 3-D, electromagnetic, relativistic PIC simulation code in collaboration with Drs. O. Buneman and T. Neubert. The code has been used to model Earth’s interaction with the solar wind [Buneman et al., 1992, 1994]. Even though the simulation parameters do not scale to realistic solar wind conditions, the results are remarkably similar to the magnetosphere-solar wind system. The code is useful now for simulation of microphysics. As supercomputers become faster and more memory becomes available it is possible that this code will produce realistic results for magnetosphere-solar wind interactions.

- **O. Buneman, T. Neubert, and K.-I. Nishikawa**, Solar wind-magnetosphere interaction as simulated by a 3-D electromagnetic particle code, *IEEE Trans. Plasma Sci.*, *20*, 810, 1992.
- **O. Buneman, K.-I. Nishikawa, and T. Neubert**, Solar wind-magnetosphere interaction as simulated by a 3D EM particle code, in *Micro and Meso Scale Phenomena in Space Plasmas*, AGU Monograph, in press, 1994.

2.3 MHD theory on magnetospheric modes and the Alfvén resonance

The propagation of MHD waves through the magnetosphere is affected by the inhomogeneous nature of the plasma density, magnetic field and temperature. As a result, waves often have resonances and turning points, e.g. the well-known Alfvén resonance expected in the plasma sheet. Resonances lead to large fields, which can be used at ionospheric altitudes as diagnostics of the outer magnetosphere, and damping of these fields leads

to particle heating and acceleration. In addition, the eigenmodes of the magnetospheric cavity, the plasma sheet etc. are affected by the inhomogeneities. Our work considered both the Alfvén wave resonance [Hansen and Goertz, 1992; Hansen and Harrold, 1994; Hansen, 1994] and eigenmodes [Harrold and Hansen, 1993].

Hansen and Goertz [1992] showed that previous treatments of the Alfvén resonance in Earth’s magnetosphere, using a severe truncation of resonant couplings between different field lines, are inconsistent and do not actually predict a narrow Alfvén resonance. Hansen and Harrold [1994] modelled the Alfvén resonance in the plasma sheet boundary layer using an inhomogeneous slab model with open field lines. Again, they find that the Alfvén resonance singularity does not occur. Instead, wave energy is absorbed over a broad region. Hansen [1994] refuted criticisms of the Hansen and Goertz paper and suggested extensions thereof.

- **P.J. Hansen and C.K. Goertz**, Validity of the field line resonance expansion, *Phys. Fluids B*, 4, 2,713, 1992.
- **P.J. Hansen and B.G. Harrold**, Parallel inhomogeneity and the Alfvén resonance 1. Open field lines, *J. Geophys. Res.*, 99, 2,429, 1994.
- **P.J. Hansen**, Response to “Comment on ‘Validity of the field line resonance expansion’ ”, *Phys. Plasmas*, 1, 1,095, 1994.

Harrold and Hansen [1994] examined whether so-called ‘vortex’ modes observed in the magnetotail can be interpreted in terms of eigenmodes of the inhomogeneous plasma sheet. They find that one eigenmode closely matches the observed phase and amplitude characteristics. This paper is being revised and resubmitted.

- **B.G. Harrold and P.J. Hansen**, Vortex eigen modes of the plasma sheet, *Geophys. Res. Lett.*, submitted, 1994.

2.4 Auroral Physics

Goertz et al. [1991b] developed a new 2-D electrostatic simulation code, the so-called Current Driven Double Layer (CUDDL), to investigate the excitation of the electrostatic ion cyclotron instability by a propagating Alfvén wave. The application was to ion cyclotron waves and electron acceleration in the presence of the large-scale current systems in the auroral region. They found that the ion cyclotron instability was indeed excited and led to the generation of solitary wave structures otherwise known as double layers. Subsequently Harrold and Nishikawa [1994] refurbished the CUDDL code and investigated solitary ion cyclotron waves and electron acceleration with application to discrete auroral arcs.

- **C.K. Goertz, T. Whelan, and K.-I. Nishikawa**, A new numerical code for simulating current driven instabilities on auroral field lines, *J. Geophys. Res.*, 96, 9579, 1991.

- **B.G. Harrold and K.-I. Nishikawa**, Excitation of the ion cyclotron instability in a discrete arc, *J. Geophys. Res.*, submitted, 1994.

2.5 Microphysics and CIV physics

Borovsky and Hansen [1991] considered the breaking of adiabatic invariants in time-dependent magnetic fields. The intended application is to particle energization during the magnetic dipolarization period near substorm onset. Detailed analysis indicates, however, that only weak breaking of adiabatic invariants occurs. This argues against the mechanism contributing significantly to the observed particle injections.

- **J.E. Borovsky and P.J. Hansen**, Breaking of the first adiabatic invariants of charged particles in time-dependent magnetic fields: computer simulations and theory, *Phys. Rev. A*, *43*, 5,605, 1991.

Lonngren et al. [1992] and Hansen and Longren [1993] considered soliton physics with the hope of applying the results to ion cyclotron solitons/double layers observed on auroral field lines.

- **K.E. Lonngren, P.J. Hansen, and T. Kuusela**, A heuristic prediction of the number of solitons that are excited by an arbitrary potential, *Physica Scripta*, *46*, 63, 1992.
- **P.J. Hansen and K.E. Lonngren**, On the Prediction of the Number of Solitons Excited by an Arbitrary Potential: An Observation from Inverse Scattering, *Physica D*, *68*, 12, 1993.

In the Critical Ionization Velocity effect (CIV) an initial seed ionization leads to an ion beam which drives lower hybrid waves, the waves resonantly accelerate electrons, and the electrons then ionize more of the cloud's gas particles in collisions, thereby setting up a feedback loop. Work on the CIV effect was pursued under the aegis of this grant in 1992 and 1993 [Moghaddam-Taaheri and Goertz, 1993; Moghaddam-Taaheri et al., 1994] since lower hybrid waves are driven by ion beams in the bow shock, magnetosheath, and perhaps the plasma sheet boundary layer. The PIC and quasi-linear codes developed were expected to be useful in these other applications too. Significant progress was made, particularly in illuminating the importance to the CIV yield of the gas cloud's finite size and the magnitude of the ambient plasma density.

- **E. Moghaddam-Taaheri and C.K. Goertz**, Numerical quasi-linear study of the critical ionization velocity phenomenon, *J. Geophys. Res.*, *98*, 1,443, 1993.
- **E. Moghaddam-Taaheri, G. Lu, C.K. Goertz, and K.-I. Nishikawa**, Particle-in-cell simulations of the Critical Ionization Velocity effect in finite size clouds, *J. Geophys. Res.*, *99*, 6,393, 1994.

A Personnel involved in Grant NAGW-1483

- Professor Chris K. Goertz, Principal Investigator 1990 - 1991 (deceased 1991).
- Professor Robert A. Smith, 1990 - 1991 (deceased 1991).
- Dr. Lin-Hua Shan, 1990 - 1991 (deceased 1991).
- Dr. Gang Lu, 1990 - 1991 (deceased 1991).
- Dr. John G. Lyon, 1990 - 1993, Principal Investigator 1991 - 1993,
- Dr. Paul Hansen, 1990 - 1995.
- Dr. Barry Harrold, 1990 - 1995.
- Dr. Ebraahim Moghaddam-Taaheri, 1990 - 1995.
- Dr. Ken-ichi Nishikawa, 1991 - 1995.
- Dr. Iver H. Cairns, 1991 - 1995, Principal Investigator 1993 - 1995.
- Mr. Bob Holdaway, 1990 - 1995.
- Mr. Xi Lin, 1990 - 1992.
- Mr. Lyle Jalbert, 1990 - 1992.

B Graduate Students funded by Grant NAGW-1483

- Lin-Hua Shan, 1990 - 1991, Ph.D. in 1990.
- Gang Lu, 1990 - 1991, Ph.D. in 1991.
- Xi Lin, 1990 - 1992, M.S. in 1992.
- Lyle Jalbert, 1990 - 1992, M.S. in 1992.
- Bob Holdaway, 1990 - 1994, M.S. in 1995.

C Papers Funded by Grant NAGW-1483

- Goertz, C.K., R.A. Smith, and L.-H. Shan, Chaos in the plasma sheet, *Geophys. Res. Lett.*, **18**, 1639, 1991a.
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